

Asymmetries in the Non-Mesonic Weak Decay of Polarized Λ -Hypernuclei

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The non-mesonic weak decay of *polarized* Λ -hypernuclei is studied for the first time by taking into account, with a Monte Carlo intranuclear cascade code, the nucleon final state interactions. A one-meson-exchange model is employed to describe the $\bar{\Lambda}N \rightarrow nN$ processes in a finite nucleus framework. The relationship between the intrinsic Λ asymmetry parameter a_Λ and the asymmetry a_Λ^M accessible in experiments is discussed. A strong dependence of a_Λ^M on nucleon final state interactions and detection threshold is obtained. Our results for a_Λ^M are consistent with ${}^{11}_\Lambda\bar{B}$ and ${}^{12}_\Lambda\bar{C}$ data but disagree with observations in ${}^5_\Lambda\bar{He}$.

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The physics of the weak decay of hypernuclei has experienced a recent important development. Due to theoretical [1–6] and experimental [7–9] progress, we are now towards a solution of the long standing puzzle [10] on the ratio, Γ_n/Γ_p , between the non-mesonic weak decay (NMWD) rates for the processes $\Lambda n \rightarrow nn$ and $\Lambda p \rightarrow np$. This has been possible mainly thanks to the study of nucleon coincidence observables [5,7]. According to the analysis of KEK data [7] made in Refs. [5,11], the Γ_n/Γ_p ratio for both ${}^5_\Lambda\bar{He}$ and ${}^{12}_\Lambda\bar{C}$ is around $0.3 \div 0.4$, in agreement with recent pure theoretical estimates [1–4]. Confirmations of these results are awaited from forthcoming experiments at DAΦNE [12] and J-PARC [13].

Despite this recent progress, the reaction mechanism for the hypernuclear NMWD is not fully understood. Indeed, an intriguing problem, of more recent origin, is open: it concerns the asymmetry of the angular emission of NMWD protons from polarized hypernuclei. This asymmetry is due to the interference between parity-violating and parity-conserving $\bar{\Lambda}p \rightarrow np$ transition amplitudes [14]. The study of the asymmetric emission of protons from polarized hypernuclei is supposed to provide information on the spin-parity structure of the $\Lambda N \rightarrow nN$ process and hence new constraints on the dynamics of the non-mesonic decay.

The intensity of protons emitted in $\bar{\Lambda}p \rightarrow np$ decays along a direction forming an angle θ with the polarization axis is given by (for details see Ref. [15]):

$$I(\theta) = I_0 [1 + \mathcal{A}(\theta)], \quad \mathcal{A}(\theta) = P_y A_y \cos \theta, \quad (1)$$

where P_y is the hypernuclear polarization and A_y the hypernuclear asymmetry parameter. Moreover, I_0 is the (isotropic) intensity for an unpolarized hypernucleus, which we normalize as the total number of primary protons produced per NMWD, $I_0 = 1/(1 + \Gamma_n/\Gamma_p)$. In the shell model weak-coupling scheme, angular momentum algebra expresses the polarization of the Λ spin, p_Λ , in terms of P_y : $p_\Lambda = P_y$ if $J = J_C + 1/2$ and $p_\Lambda = -P_y J/(J + 1)$ if $J = J_C - 1/2$, J (J_C) being

the hypernucleus (nuclear core) total spin. By introducing the intrinsic Λ asymmetry parameter, $a_\Lambda = A_y$ if $J = J_C + 1/2$ and $a_\Lambda = -A_y(J + 1)/J$ if $J = J_C - 1/2$, one obtains: $\mathcal{A}(\theta) = p_\Lambda a_\Lambda \cos \theta$. In the hypothesis that the weak-coupling scheme provides a realistic description of the hypernuclear structure, a_Λ can be interpreted as the intrinsic Λ asymmetry parameter for the elementary process $\bar{\Lambda}p \rightarrow np$ taking place inside the hypernucleus. This scheme is known to be a good approximation for describing the ground state of Λ -hypernuclei and previous calculations [3,15] have proved that, thanks to the large momentum transfer, the non-mesonic decay is not much sensitive to nuclear structure details.

Nucleon final state interactions (FSI), subsequent to the NMWD, are expected to modify the weak decay intensity of Eq. (1). Experimentally, one has access to a proton intensity $I^M(\theta)$ which is generally assumed to have the same θ -dependence as $I(\theta)$:

$$I^M(\theta) = I_0^M [1 + p_\Lambda a_\Lambda^M \cos \theta]. \quad (2)$$

Then, the observable asymmetry a_Λ^M is determined as:

$$a_\Lambda^M = \frac{1}{p_\Lambda} \frac{I^M(0^\circ) - I^M(180^\circ)}{I^M(0^\circ) + I^M(180^\circ)}. \quad (3)$$

Concerning the determination, from data, of the intrinsic Λ asymmetry parameter a_Λ , it is important to stress the following two questions originated by nucleon FSI: i) one should demonstrate (experimentally and/or theoretically) that the angular dependence of $I^M(\theta)$ employed in experimental analyses is realistic; ii) if this is verified, one should investigate the relationship between a_Λ and a_Λ^M , since a_Λ^M is expected to depend on experimental conditions such as the proton detection threshold and the considered hypernucleus.

The $n(\pi^+, K^+)\Lambda$ reaction is able to produce Λ hypernuclear states with a sizeable amount of spin-polarization [16] preferentially aligned along the axis normal to the reaction plane. Until now, four KEK experiments measured the proton asymmetric emission from polarized

Λ -hypernuclei. The 1992 KEK-E160 experiment [17], which studied p -shell hypernuclei, suffered from large uncertainties: only poor statistics and energy resolution could be used; moreover, the values of the Λ polarization p_Λ needed to determine the asymmetry a_Λ^M , had to be evaluated theoretically. More recently, a_Λ^M was measured by KEK-E278 [18] for the decay of ${}^5_\Lambda\bar{\text{He}}$. The values of p_Λ used to obtain a_Λ^M were determined by observing the asymmetry, $\mathcal{A}^{\pi^-} = p_\Lambda a_\Lambda^{\pi^-}$, in the emission of negative pions in the ${}^5_\Lambda\bar{\text{He}}$ mesonic decay, after assuming [19] $a_\Lambda^{\pi^-}$ to be equal to the value for the free $\Lambda \rightarrow \pi^- p$ decay, $a_\Lambda^{\pi^-} = -0.642 \pm 0.013$. A similar measurement of p_Λ is very difficult, instead, for p -shell hypernuclei due to their small branching ratio and expected asymmetry \mathcal{A}^{π^-} for the mesonic decay; even the recent and more accurate experiment KEK-E508 [20] had to resort to theoretical estimates [21] for the Λ polarization in ${}^{12}_\Lambda\bar{\text{C}}$ and ${}^{11}_\Lambda\bar{\text{B}}$. Recently, a_Λ^M was measured again for ${}^5_\Lambda\bar{\text{He}}$, by KEK-E462 [20], but with improved statistics.

In Table I we report the results for a_Λ^M obtained by the above mentioned experiments, together with recent theoretical estimates for a_Λ . While theoretical models predict negative a_Λ values [22], with a moderate dependence on the hypernucleus, the experiments seem to favor negative values for $a_\Lambda^M({}^{12}_\Lambda\bar{\text{C}})$ but positive values for $a_\Lambda^M({}^5_\Lambda\bar{\text{He}})$.

Concerning the above comparison between theory and experiment, it is important to stress that, while one predicts $a_\Lambda({}^5_\Lambda\bar{\text{He}}) \simeq a_\Lambda({}^{12}_\Lambda\bar{\text{C}})$, there is no known reason to expect this approximate equality to be valid for a_Λ^M . Indeed, the relationship between $I(\theta)$ of Eq. (1) and $I^M(\theta)$ of Eq. (2) can be strongly affected by FSI of the emitted protons: this fact prevents establishing a direct relation between a_Λ and a_Λ^M and to make a direct comparison among results for these quantities. In order to overcome this problem, in the present work we evaluate the effects of the nucleon FSI on the NMWD of ${}^5_\Lambda\bar{\text{He}}$, ${}^{11}_\Lambda\bar{\text{B}}$ and ${}^{12}_\Lambda\bar{\text{C}}$ and we perform the first theoretical estimate of a_Λ^M .

The $\Lambda N \rightarrow nN$ weak transition is described with the one-meson-exchange potential of Ref. [3], which accounts for the exchange of π , ρ , K , K^* , ω and η mesons and well reproduces the new Γ_n/Γ_p ratios extracted from KEK data [7] via the weak-interaction-model independent analysis of Refs. [5,11]. The strong final state interactions acting between the weak decay nucleons are taken into account through a scattering nN wave function from the Lippmann-Schwinger equation obtained with the Nijmegen Soft-Core NSC97 (versions “a” and “f”) potentials [25]. The two-nucleon stimulated process $\Lambda NN \rightarrow nNN$ [10,26] is safely neglected in our analysis. The fraction of protons from two-nucleon induced decays which escapes from the nucleus with an energy above the typical detection threshold is predicted [5] to be small with respect to the fraction originating from $\Lambda N \rightarrow nN$. The propagation of primary (i.e., weak decay) and secondary nucleons (due to FSI) inside the residual nucleus

is simulated with the Monte Carlo code of Ref. [27].

In Fig. 1 (2) we show the proton intensity obtained for the non-mesonic decay of ${}^5_\Lambda\bar{\text{He}}$ (${}^{12}_\Lambda\bar{\text{C}}$) using the full one-meson-exchange model with the NSC97f potential (the NSC97a potential predicts very similar results). We note that the hypernuclear polarization has been taken to be $P_y = 1$ in these figures, so that the hypernuclear asymmetry parameter A_y can be directly extracted from the values of the weak decay intensity at $\theta = 0^\circ$ and $\theta = 180^\circ$. The continuous histograms correspond to the intensity $I(\theta)$ of primary protons [Eq. (1)]. The inclusion of the nucleon FSI strongly modifies the spectra. With vanishing kinetic energy detection threshold, T_p^{th} , the intensities are strongly enhanced, especially for ${}^{12}_\Lambda\bar{\text{C}}$. For $T_p^{\text{th}} = 30$ or 50 MeV, the spectra are closer to $I(\theta)$, although with a different slope, reflecting the fact that FSI are responsible for a substantial fraction of outgoing protons with energy below these thresholds. A further reduction of $I^M(\theta)$ is observed for $T_p^{\text{th}} = 70$ MeV.

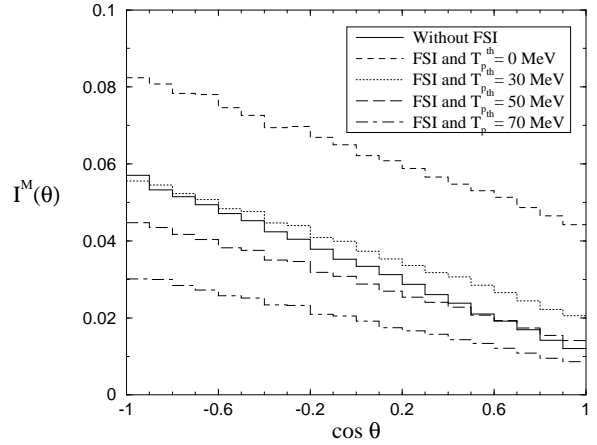


FIG. 1. Angular intensity of protons emitted per NMWD of ${}^5_\Lambda\bar{\text{He}}$. See text for details.

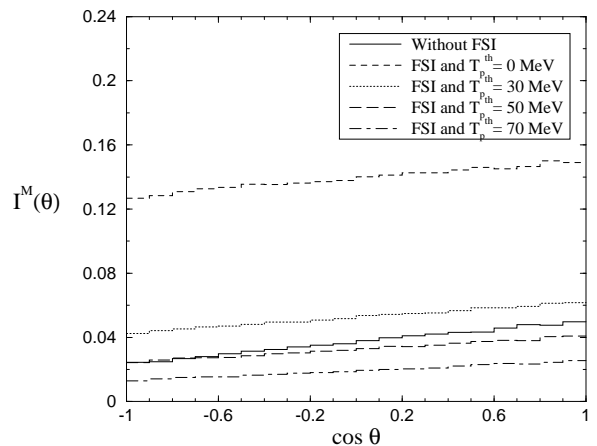


FIG. 2. Same of Fig. 1 for ${}^{12}_\Lambda\bar{\text{C}}$. See text for details.

It is evident from Figs. 1 and 2 that the simulated intensities turn out to be well fitted by the linear law in $\cos\theta$ of Eq. (2). We can thus estimate a_Λ^M by using Eq. (3) with $p_\Lambda = 1$ for ${}^5_\Lambda\bar{\text{He}}$, $p_\Lambda = -1/2$ for ${}^{12}_\Lambda\bar{\text{C}}$ and $p_\Lambda = -5/7$ for ${}^{11}_\Lambda\bar{\text{B}}$. To do this, $I^M(0^\circ)$ ($I^M(180^\circ)$) is evaluated numerically as the proton intensity in the bin with $\cos\theta \in [0.9, 1]$ ($\in [-1, -0.9]$). In Table II (III) we show our predictions for I_0 , I_0^M , a_Λ and a_Λ^M for ${}^5_\Lambda\bar{\text{He}}$ (${}^{11}_\Lambda\bar{\text{B}}$ and ${}^{12}_\Lambda\bar{\text{C}}$). They refer to the one-pion-exchange (OPE) and the full one-meson-exchange (OME) models, both using the NSC97f potential. As a result of the nucleon FSI, $|a_\Lambda| \gtrsim |a_\Lambda^M|$ for any value of the proton threshold: when $T_p^{\text{th}} = 0$, $a_\Lambda/a_\Lambda^M \simeq 2$ for ${}^5_\Lambda\bar{\text{He}}$ and $a_\Lambda/a_\Lambda^M \simeq 4$ for ${}^{11}_\Lambda\bar{\text{B}}$ and ${}^{12}_\Lambda\bar{\text{C}}$; $|a_\Lambda^M|$ increases with T_p^{th} and $a_\Lambda/a_\Lambda^M \approx 1$ for $T_p^{\text{th}} = 70$ MeV in all cases.

In Tables II and III our results are compared with the preliminary KEK data of Ref. [20], which correspond to a proton detection threshold varying (from event to event) between 30 and 50 MeV. For these conditions, we obtain OME asymmetries a_Λ^M rather independent of the hypernucleus and in the range $-0.55 \div -0.37$. The a_Λ^M values are smaller in size than the corresponding asymmetries before FSI effects, a_Λ , by 25 to 50%. It is evident that our OME results are in agreement with the ${}^{12}_\Lambda\bar{\text{C}}$ datum, barely compatible with the ${}^{11}_\Lambda\bar{\text{B}}$ datum and inconsistent with the ${}^5_\Lambda\bar{\text{He}}$ datum. One also sees that the OPE asymmetries are systematically smaller, though less realistic from the theoretical point of view, than the OME ones.

In view of the above large discrepancy, we have proved, numerically, that positive a_Λ^M values —such as the ones measured at KEK for ${}^5_\Lambda\bar{\text{He}}$ — can be obtained only if positive values for the intrinsic asymmetry a_Λ are enforced in the weak decay intensity $I(\theta)$ of Eq. (1): indeed, a_Λ and a_Λ^M always have the same sign. However, unless there are large SU(3) violations in the coupling constants, it seems unlikely that the meson-exchange models give rise to a positive or vanishing value of the intrinsic Λ asymmetry. Indeed, we have analyzed the origin of the large and negative asymmetry parameter in the one-meson-exchange model of Ref. [3], by calculating the two-body $\Lambda N(^{2S+1}L_J) \rightarrow n N(^{2S'+1}L'_J)$ amplitudes a, b, c, d, e, f for ${}^5_\Lambda\bar{\text{He}}$, and determining the intrinsic asymmetry through the following relation [28]:

$$a_\Lambda = \frac{2\sqrt{3} \operatorname{Re} [ae^* - b(c - \sqrt{2}d)^*/\sqrt{3} + f(\sqrt{2}c + d)^*]}{|a|^2 + |b|^2 + 3[|c|^2 + |d|^2 + |e|^2 + |f|^2]}.$$

In a framework with real ΛN and nN wave functions, the OPE mechanism produces a large and negative a_Λ value due, mainly, to an interference between a large and negative tensor amplitude d (${}^3S_1 \rightarrow {}^3D_1$) and the parity violating amplitudes b (${}^1S_0 \rightarrow {}^3P_0$) and f (${}^3S_1 \rightarrow {}^3P_1$), which are both positive and of moderate size. The inclusion of kaon exchange modifies this picture drastically. Destructive interference with the pion in the tensor channel re-

duces the d amplitude by a factor of 4, which would lead to a sensitive decrease in the size of a_Λ . However, the negative a (${}^1S_0 \rightarrow {}^1S_0$) and c (${}^3S_1 \rightarrow {}^3S_1$) amplitudes become one order of magnitude larger in size. Their interference with the positive e (${}^3S_1 \rightarrow {}^1P_1$) and f (${}^3S_1 \rightarrow {}^3P_1$) amplitudes end up producing a final value for a_Λ which is even 50% larger in size than for OPE alone. The inclusion of the heavier mesons does not change this qualitative behavior.

Summarizing, we have seen how FSI are an important ingredient when studying the NMWD of polarized hypernuclei. The first relationship between the intrinsic asymmetry a_Λ and the observable asymmetry a_Λ^M has been established. Unfortunately, not even an analysis including FSI can explain the present experimental data. From the theoretical point of view, we believe it unlikely that new reaction mechanisms are responsible for the present discrepancies. Only small and positive values of a_Λ , not predicted by any existing model, could reduce a_Λ^M to small and positive values.

In order to avoid possible statistical fluctuations of the data, new and/or improved experiments, better establishing the sign and magnitude of a_Λ^M for s - and p -shell hypernuclei (possibly also exploring the full angular region of the proton intensities) will be important to provide a guidance for a deeper understanding of the $\Lambda N \rightarrow nN$ process in nuclei. The study of the inverse reaction $\bar{p}n \rightarrow p\Lambda$ [29] should also be encouraged since it could further supply richer and cleaner information on the lambda-nucleon weak interaction and especially on the Λ spin-dependent observables [28]. In our opinion, a closer collaboration among theoreticians and experimentalists (as the one experienced in the recent analyses of the Γ_n/Γ_p ratio) is also desirable to disclose the origin of the asymmetry puzzle.

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TABLE I. Theoretical and experimental determinations of the asymmetry parameters (a_Λ and a_Λ^M , respectively). The predictions for a_Λ have been obtained with different weak transition potentials.

Ref. and Model	${}^5_\Lambda\vec{\text{He}}$	${}^{12}_\Lambda\vec{\text{C}}$
K. Sasaki et al. [1]		
$\pi + K$ + Direct Quark	-0.68	
A. Parreño et al. [3]		
$\pi + \rho + K + K^* + \omega + \eta$	-0.68	-0.73
K. Itonaga et al. [23]		
$\pi + K + \omega + 2\pi/\rho + 2\pi/\sigma$	-0.33	
C. Barbero et al. [24]		
$\pi + \rho + K + K^* + \omega + \eta$	-0.54	
A. Parreño et al. [6]		
$\pi + K$ + contact terms	0.24	0.21
KEK-E160 [17]		$-0.9 \pm 0.3^*$
KEK-E278 [18]	0.24 ± 0.22	
KEK-E508 (prel.) [20]		-0.44 ± 0.32
KEK-E462 (prel.) [20]	0.07 ± 0.08	

* This result correspond to the weighted average (discussed on pag. 95 of Ref. [10]) among different p -shell hypernuclear data.

TABLE II. Proton intensities and asymmetry parameters for the non-mesonic weak decay of ${}^5_\Lambda\text{He}$.

Model	I_0^M	a_Λ^M
OPE		
Without FSI (I_0, a_Λ)	0.92	-0.25
FSI and $T_p^{\text{th}} = 0$ MeV	1.56	-0.12
FSI and $T_p^{\text{th}} = 30$ MeV	0.99	-0.18
FSI and $T_p^{\text{th}} = 50$ MeV	0.78	-0.20
FSI and $T_p^{\text{th}} = 70$ MeV	0.52	-0.20
OME		
Without FSI (I_0, a_Λ)	0.69	-0.68
FSI and $T_p^{\text{th}} = 0$ MeV	1.27	-0.30
FSI and $T_p^{\text{th}} = 30$ MeV	0.77	-0.46
FSI and $T_p^{\text{th}} = 50$ MeV	0.59	-0.52
FSI and $T_p^{\text{th}} = 70$ MeV	0.39	-0.55
KEK-E462 (prel.) [20]		0.07 ± 0.08

TABLE III. Same as in Table II for ${}^{11}_\Lambda\vec{\text{B}}$ and ${}^{12}_\Lambda\vec{\text{C}}$.

Model	${}^{11}_\Lambda\vec{\text{B}}$ I_0^M	a_Λ^M	${}^{12}_\Lambda\vec{\text{C}}$ I_0^M	a_Λ^M
OPE				
Without FSI (I_0, a_Λ)	0.91	-0.30	0.93	-0.34
FSI and $T_p^{\text{th}} = 0$ MeV	2.84	-0.08	3.15	-0.09
FSI and $T_p^{\text{th}} = 30$ MeV	1.16	-0.17	1.22	-0.20
FSI and $T_p^{\text{th}} = 50$ MeV	0.76	-0.24	0.78	-0.28
FSI and $T_p^{\text{th}} = 70$ MeV	0.47	-0.32	0.46	-0.38
OME				
Without FSI (I_0, a_Λ)	0.70	-0.81	0.75	-0.73
FSI and $T_p^{\text{th}} = 0$ MeV	2.44	-0.18	2.78	-0.16
FSI and $T_p^{\text{th}} = 30$ MeV	0.96	-0.39	1.05	-0.37
FSI and $T_p^{\text{th}} = 50$ MeV	0.62	-0.55	0.65	-0.51
FSI and $T_p^{\text{th}} = 70$ MeV	0.38	-0.70	0.38	-0.65
KEK-E508 (prel.) [20]		0.11 ± 0.44		-0.44 ± 0.32